

# Increasing Carbon Sequestration through Enhanced Stand Establishment Practices: Nursery Nutrient Loading





# **Increasing Carbon Sequestration through Enhanced Stand Establishment Practices: Nursery Nutrient Loading**

V.R. Timmer and Y. Teng

Faculty of Forestry  
University of Toronto  
33 Willcocks Street  
Toronto, Ontario  
M5S 3B3

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Fax: (705) 946-2030  
E-mail: [information.ofri@mnr.gov.on.ca](mailto:information.ofri@mnr.gov.on.ca)

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### Abstract

Improving early performance of outplanted tree nursery stock under stressful and competitive field conditions is crucial to the success of establishing new forests. Vigorous growth in juvenile plantations can last decades, and seedlings raised under steady-state nutrient loading conditions in the nursery may outperform conventional seedlings in early growth after outplanting. We estimated the long-term potential of enhanced reforestation using nutrient-loaded seedlings to increase carbon sequestration using black spruce (*Picea mariana* [Mill.] B.S.P.) plantations in northern Ontario as a case study. The study involved widely applied mathematical stand modelling procedures. Published early growth data of outplanted nutrient-loaded and conventional seedlings were pooled to calibrate and select the fittest model for predicting growth of maturing plantations. Tree height estimates were converted to biomass and carbon content to express post-planting response of nursery nutrient loading on future plantation productivity and carbon sequestration. Model results indicate that plantations generated from nutrient-loaded seedlings on a typical hardwood/mixedwood site in northern Ontario may sequester carbon at  $143.1 \text{ Mg ha}^{-1}$  in a normal rotation, which is 31.9% greater than that of plantations generated from conventional seedlings ( $108.6 \text{ Mg ha}^{-1}$ ).

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## Introduction

Global warming is a major environmental issue that concerns scientists, governments, and the general public all over the world. An important driver is human-caused increases in carbon dioxide ( $\text{CO}_2$ ) in the atmosphere. Forests are important sinks of carbon. Humans can enhance  $\text{CO}_2$  removal from the atmosphere by increasing photosynthesis by forest trees. Increasing forest coverage and accelerating tree growth are two ways of sequestering additional  $\text{CO}_2$ . Hence, there is increased interest in modifying forestry practices to increase tree growth, particularly at the juvenile plantation stage, so carbon can be sequestered early in the forest rotation (Papadopol 2000, Parker et al. 2000).

Using black spruce as a case study, we examined the use of nutrient-enriched or *nutrient-loaded* nursery stock to enhance stand establishment and increase carbon sequestration in plantation forests. Mathematical models were used to predict future growth and biomass production (or the amount of carbon absorbed from the atmosphere and used to produce wood) from measured early growth response. The effects of nutrient loading on carbon sequestration were estimated by comparing potential productivity of plantations originating from nutrient-loaded seedlings with that of conventional plantations.

## Objectives

The objectives of this project were to:

1. Examine relationships between nursery fertilization, more specifically nutrient loading, and post-planting tree growth
2. Convert tree growth to tree biomass and tree carbon content to express differences in post-planting nursery fertilization effects
3. Calculate area-based increases in carbon sequestration per rotation based on more rapid crown closure and greater stand productivity at harvest age
4. Examine data and other published literature for evidence that nursery stock properties can affect stand growth past crown closure

## Literature Review

### Climate change impact on forests and forestry

Increased frequency and intensity of extreme weather events, such as sand storms, ice storms, hurricanes, droughts, and floods, have been linked to human caused greenhouse effects or climate change (Francis and Hengeveld 1998, McCarthy et al. 2001). The primary cause is increased  $\text{CO}_2$  in the atmosphere. This important carbon-containing compound flows between the sources and sinks during carbon cycling (Schimel et al. 1994). Its concentration in the air represents the balance between its release from carbon sources and deposit to carbon sinks. It is estimated that human activities caused  $\text{CO}_2$  concentration in the air to increase more than 25% in the last century, mainly by burning fossil fuels (80%) but also by clearing forests (20%) (Bolin 1983, Schimel et al. 1994, Houghton et al. 2001).

Managing carbon sinks and sources has attracted research interest and public attention because of the cultural, social, economic, and ecological consequences of global warming. Sophisticated computer models have been developed to predict future climate changes (Lau et al. 1996) and subsequent environmental scenarios (Rizzo and Wilken 1992, Scott et al. 2002). Scientists have also assessed the potential impact on regional forest ecosystems and have proposed changes in forest management to sequester carbon if climate change continues (see Parker et al. 2000). Since  $\text{CO}_2$  is an essential raw material of photosynthesis, global warming and atmospheric  $\text{CO}_2$  enrichment will stimulate carbon fixation by plants, although inherent soil fertility may eventually limit carbon sequestration in soil and forest ecosystems (Oren et al. 2001, Schlesinger and Lichter 2001). Increased atmospheric  $\text{CO}_2$  may also indirectly increase forest disturbances by insect infestations (Safranyik 1990, Fleming and Volney 1995), forest fires (Wotton and Flannigan 1993, Simard 1997, Stocks et al. 1998), and extreme weather events. Rizzo and Wilken (1992) warned that under a doubled  $\text{CO}_2$  scenario, Ontario's current boreal forest would gradually be displaced by temperate forest and would be slow to migrate north into the tundra because of the poor soils and permafrost.

The scientific community generally agrees that rate of increase in atmospheric CO<sub>2</sub> concentrations must be slowed and that the primary way to achieve this is to restrict the burning of fossil fuels. However, improved economic development is still the main goal pursued by most countries and alternative sources of energy are unlikely to replace fossil fuels in the near term. Thus, although global warming is inevitable, the extent of the change can be reduced if the increase in atmospheric CO<sub>2</sub> concentration is minimized. Using forested ecosystems to sequester carbon is one option available to Canada under the auspices of the Kyoto Protocol (Papadopol 2000, Parker et al. 2000). Increased afforestation and reforestation in Canada has significant long-term potential as a carbon reduction tool because thousands of hectares are lost each year due to poor restocking of commercial tree species (Honer et al. 1991) that fail to regenerate naturally after harvest and other long-term disturbances such as urbanization.

### Plantation establishment and vegetation control

In Canada, successful establishment of conifer plantations depends on effective control of competing vegetation (Burton 1993, Wagner et al. 2001). The first few growing seasons after outplanting are especially critical for spruce plantations (Burdett et al. 1984), because the seedlings are sensitive to planting shock and vegetative competition. Historically, forest managers have used site preparation by chemical herbicides, mechanical (scarification) methods, and prescribed fire to suppress competing vegetation (CCFM 2002). These practices are usually efficient but there can be negative consequences, including disturbances to wildlife and accelerated CO<sub>2</sub> emissions from mechanically mixed soil and litter or burning. In addition, public concern about using chemicals in forest management can make the use of herbicides difficult (Wagner et al. 1998). A more socially and perhaps ecologically friendly alternative is to increase the competitiveness of crop trees by enhancing their growth so that they are not suppressed by surrounding vegetation (Burdett et al. 1984, Newton et al. 1993).

### Nursery stock properties and plantation performance

To be more competitive with other plant species, planting stock is usually grown to meet certain morphological and physiological criteria, such as larger size, optimum shoot/root ratio, optimum nutrition, and well-hardened shoots (Burdett et al. 1984, Duryea and McClain 1984, Newton et al. 1993, South and Mason 1993). Fertilization is one of the most effective ways to improve seedling quality in nursery culture. A review by van den Driessche (1991) showed that nursery fertilization generally enhanced seedling performance after planting (Table 1), but negative responses, especially reduced survival, were also noted (Duryea and McClain 1984). van den Driessche (1991) concluded that late-season fertilization in the nursery and the use of larger seedlings usually resulted in better establishment, since planted seedlings contained more nutrients for growth. Nutritionally enhanced seedlings also used water resources more efficiently (van den Driessche 1991). Until the mid-1980s, bareroot seedlings represented at least half of the nursery stock planted in Ontario; large, nutritionally enhanced seedlings were produced by implementing intensive bareroot nursery cultural practices, such as fertilization, spacing control, root pruning, and transplanting (Armson 1968, Armson and Sadreika 1974, van den Driessche 1984). Seedlings produced using intensive bareroot cultural techniques grew better than most container seedlings after outplanting (Fleming and Wood 1996, South et al. 2001). However, for economic and political reasons, bareroot seedling production in Ontario has been almost completely phased out and container seedlings comprise about 99% of stock produced for reforestation (Mohammed et al. 2001). Sutherland and Day (1988) summarized Canadian literature relating container volume and size to outplanting survival and growth of white spruce (*Picea glauca* [Moench] Voss), black spruce, and jack pine (*Pinus banksiana* Lamb) and concluded that larger containers produced larger seedlings, which in turn increased growth after outplanting. However, large seedlings cost more to produce, and to remain economically viable, nursery owners are continually challenged to produce younger and smaller seedlings that are still competitive after outplanting.

Table 1. Effects of nursery fertilization on conifer tree outplanting performance<sup>a</sup> documented in the literature.

| Species                                         | Years of growth |         | Fertilizer nutrients  | Response <sup>b</sup> |        | Source                     |
|-------------------------------------------------|-----------------|---------|-----------------------|-----------------------|--------|----------------------------|
|                                                 | Nursery         | Forest  |                       | Survival              | Height |                            |
| ----- Bareroot seedlings -----                  |                 |         |                       |                       |        |                            |
| Jack pine                                       | 2               | 7       | Inorganic             | +                     | +      | Stoeckeler and Jones 1957  |
| Caribbean pine                                  | 0.5             | 0.6     | N                     | +                     | +-     | Solberg 1978               |
| Lodgepole pine                                  | 2               | 3       | N                     | 0                     | +-     | Benzian et al. 1974        |
| Shortleaf pine                                  | 2               | 2       | N                     | 0                     | +      | van den Driessche 1982     |
| Longleaf pine                                   | 1               | 8       | N P K Ca Mg           | +                     | +      | Hinsely and Maki 1980      |
| Red pine                                        | 2               | 2       | N P K                 | +                     | +      | Wilde et al. 1940          |
| Red pine                                        | 3               | 5       | N                     | +-                    | 0      | Mullin and Bowdery 1978    |
| Eastern white pine                              | 3               | 5       | N P K                 | -                     | 0      | Mullin and Bowdery 1977    |
| Scotch pine                                     | 2               | 2       | N P K                 | +                     | +      | Wilde et al. 1940          |
| Norway spruce                                   | 2               | 3       | N                     | 0                     | 0      | Benzian et al. 1974        |
| White spruce                                    | 3               | 5       | N P K                 | 0                     | +      | Morgan 1984                |
| White spruce                                    | 3               | 7       | Inorganic             | +                     | 0      | Stoeckeler and Jones 1957  |
| Sitka spruce                                    | 2               | 4       | N                     | 0                     | +      | Benzian et al. 1974        |
| Sitka spruce                                    | 2               | 3       | N                     | +                     | +      | van den Driessche 1982     |
| Douglas-fir                                     | 2               | 5       | N                     | +                     | +      | Anderson and Gessel 1966   |
| Douglas-fir                                     | 2               | 6       | Organic and inorganic | +                     | +      | Smith et al. 1966          |
| Douglas-fir                                     | 2               | 2       | N                     | +                     | +      | van den Driessche 1980     |
| Douglas-fir                                     | 2               | 3       | N                     | +                     | 0+     | van den Driessche 1982     |
| ----- Container seedlings -----                 |                 |         |                       |                       |        |                            |
| Lodgepole pine                                  | 1, 1.5          | 1       | Inorganic             | 0                     | +      | Endean and Hocking 1973    |
| White spruce                                    | 1.5             | 1       | Inorganic             | +                     | +      | Hocking and Endean 1973    |
| ----- Nutrient-loaded container seedlings ----- |                 |         |                       |                       |        |                            |
| White spruce                                    | 1               | 1       | N P K                 | +                     | +      | MacAlister and Timmer 1998 |
| Black spruce                                    | 1               | 1, 2, 4 | N P K                 | +                     | +      | Malik 1998                 |
| Black spruce                                    | 1               | 1, 2, 4 | N P K                 | +                     | +      | Malik and Timmer 1996      |
| Black spruce                                    | 1               | 5       | N P K                 | +                     | +      | Timmer 1999                |

<sup>a</sup> Modified from van den Driessche (1991)<sup>b</sup> Where + means positive, - means negative, and 0 means no response

### Nutrient loading promotes seedling competitiveness

To produce competitive nursery stock, a relatively new fertilization technique called *nutrient loading* was developed (Timmer and Munson 1991, Timmer and Aidelbaum 1996). The approach involves enriching or "loading" seedlings with nutrients during nursery culture to provide reserves for use after outplanting. Under conventional regimes, fertilizers are applied at constant dose rates throughout the cultural period, so internal nutrient concentrations are continuously diluted as seedlings grow. These rates of fertilization are not synchronized to increase with the exponential growth that occurs in young seedlings.

Nutrient-loaded seedlings receive exponentially increasing doses (Timmer and Aidelbaum 1996) to match seedling growth, so that internal nutrient concentrations remain stable and constant with time to achieve *steady-state nutrition* (Ingestad and

Lund 1986). Steady-state nutrition occurs in naturally regenerating conifer seedlings (Munson and Bernier 1993); hence, one of the benefits of steady-state nutrient culture is that seedlings are nutritionally preconditioned for outplanting. Another advantage is seedlings are fed with much more fertilizer as a result of the exponential delivery schedule, causing a progressive buildup of nutrients in the crop and thus inducing "luxury consumption" without increasing biomass significantly.

Traditionally, luxury consumption has been considered a waste of fertilizer, but in nutrient loading ensures that seedlings accumulate ample nutrient reserves that can be remobilized under nutrient stress and used for new growth after planting (MacAlister and Timmer 1998, Malik and Timmer 1995, 1996, 1998). Since the seedlings are exposed gradually and exponentially to increased fertility, they are acclimated to high internal nutrient status, avoiding any toxic effects of high nutrient input.

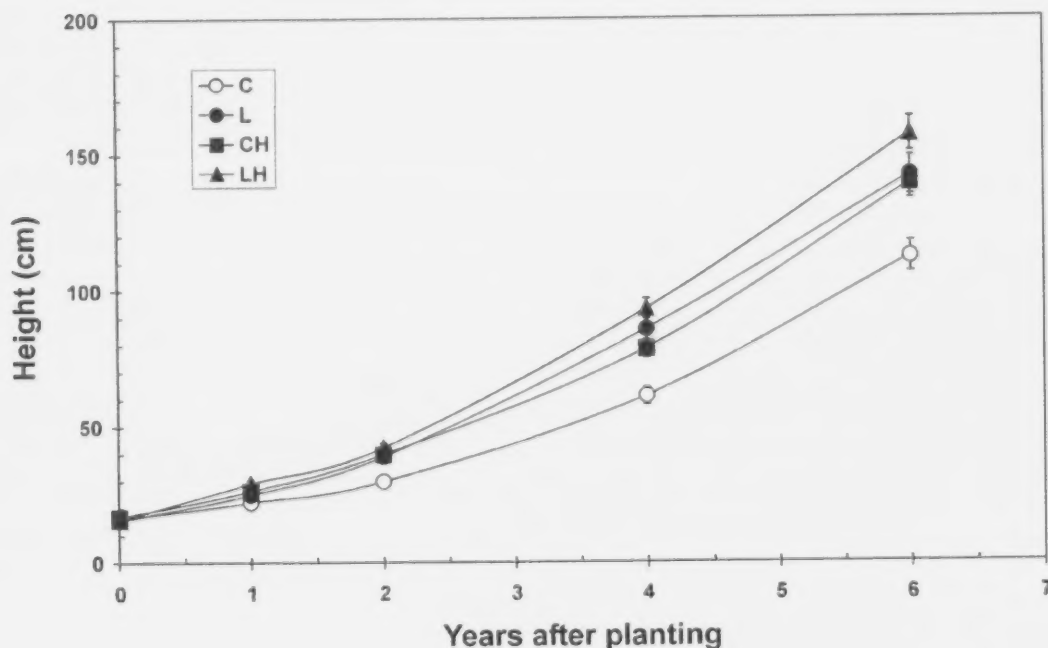


**Figure 1.** Effect of conventional fertilization (C), nutrient loading (L), herbicide (H), or nutrient loading plus herbicide (LH) on early growth of black spruce plantations. Note nutrient-loaded seedlings matched height growth of conventional fertilization plus herbicide treated (CH) trees.

## Early growth of nutrient-loaded seedlings

Field trials have shown that nutrient-loaded seedlings grow faster than conventionally raised seedlings with or without herbicide (Malik and Timmer 1996, Malik 1998, Timmer 1999) (Figure 1). Combining nutrient loading with herbicide (LH) resulted in the greatest height growth. Furthermore, 6 years after planting, nutrient-loaded seedlings on weedy sites were about as tall as herbicide-treated conventional seedlings (Figure 1), indicating that nutrient loading can replace herbicide use in young plantations. Early growth rates were lower than the tree responses reported by Fleming and Woods (1996) (Figure 2). However, growth rates were similar to those (Figure 3) derived from plantations that Payandeh and Wang (1995) established in the same part of northern Ontario (Table 2). Krumlik and Bergerud (1985) and South and Mason (1993) showed that fast growth in early plantation development may persist into later years; thus, the

superior growth in nutrient-loaded seedlings is likely to persist. Nutrient-loaded seedlings may follow steeper growth curves than those of conventional seedlings before levelling off at the time of crown closure, allowing maximum stand biomass to be reached sooner. Consequently, the stands can be harvested earlier. In turn, more  $\text{CO}_2$  will be removed from the atmosphere earlier in the life of the stand. We adopted this assumption when estimating potential carbon sequestration of nutrient-loaded seedlings.

## Methods

An outline of the procedures used to assess the effects of nutrient loading on plantation black spruce carbon sequestration is shown in Table 3. We used published growth models for black spruce, but because there is no existing model linking forest age to stand carbon, we separated the calculation into several steps.

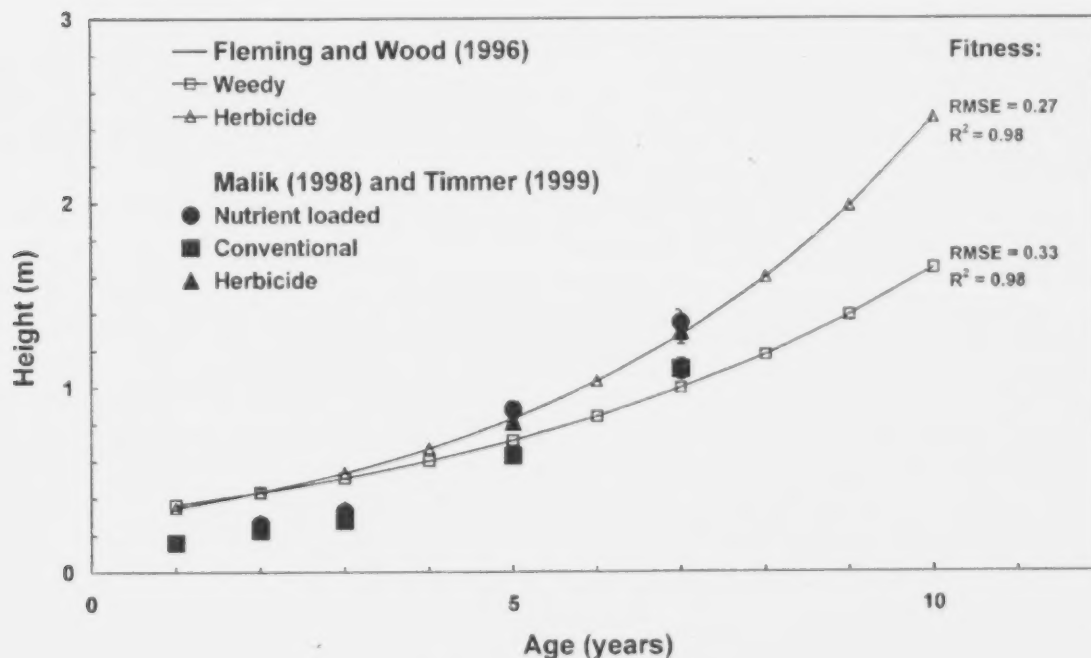


Figure 2. Height growth of young black spruce reported by Malik (1998) and Timmer (1999) compared with plantation performance recorded by Fleming and Wood (1996) in northern Ontario. RMSE = root mean square error.

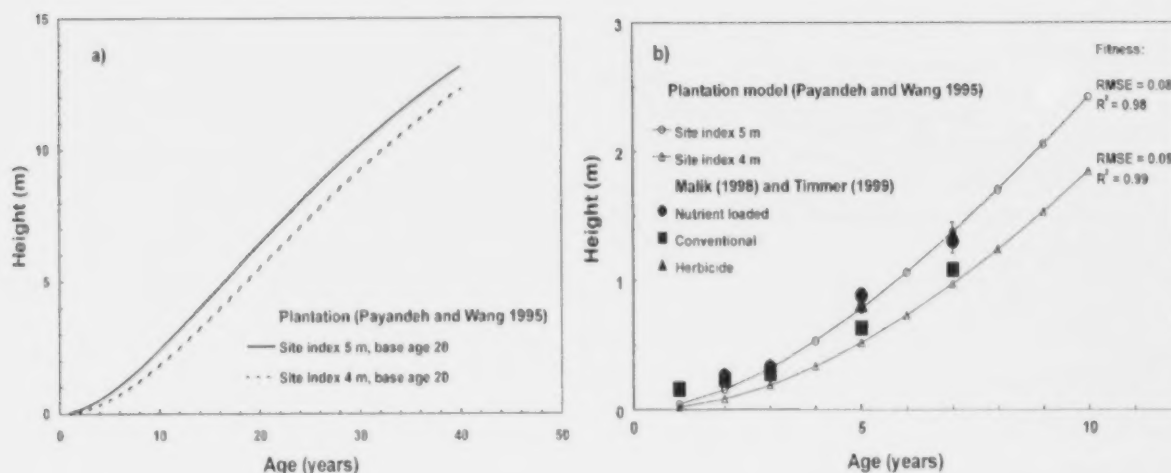


**Figure 3.** a) Site index curves for black spruce plantations in northern Ontario generated by Payandeh and Wang (1995) and b) height growth of young black spruce reported by Malik (1998) and Timmer (1999) compared with plantation performance recorded by Payandeh and Wang (1995) in Northern Ontario. RMSE = root mean square error.

### Plantation performance of nutrient-loaded seedlings

As nutrient loading is a relatively new system for fertilizing seedlings (Timmer and Munson 1991, Timmer and Aidelbaum 1996), published field performance data for nutrient-loaded seedlings are limited to results for young stands. In early 1996, Malik and Timmer (1996) first reported that nutrient-loaded seedlings grew faster than conventional seedlings in the first and second year after planting (Figure 1). This was followed by Malik (1998) and Timmer (1999) who reported that growth after four and six years was greater than that of non-loaded plantations established at the same time. We used data from these field trials, in which both nutrient-loaded and conventional seedlings were outplanted and measured for height at the first, second, fourth and sixth years after planting, to develop best fit models for future productivity and carbon sequestration potential. To assess representativeness of the data, we compared early growth measured for black spruce reported in other studies in the vicinity (Table 2) with those from Malik (1998) and Timmer (1999).

### Predicting long-term growth by site index models

Site index models are widely used by foresters to determine the relative productivity of a forest site (Davis and Johnson 1987). In natural stands, this index is generally a measure of the height of a free-growing, uninjured, dominant, or co-dominant tree of a given species at a base age. In tree plantations, improving establishment through intensive silvicultural practices such as site preparation, vegetation control, and use of high-quality seedlings may shorten rotations and increase yields (Proe et al. 1994, see Figure 4). In Ontario, the most commonly used site index model is Plonski's (1981) Normal Yield Table (Figure 5). However, Plonski's models were developed for natural stands and are not applicable for trees younger than 20 years. In addition, tree growth is usually more uniform in plantations than in forest stands. Hence, Payandeh and Wang (1995) developed site index models for plantation forestry. They measured 23 conifer plantations in Ontario and constructed site index models for 3 species (black spruce, white spruce, and jack pine) (Figure 3). The models are polynomial equations:

$$H = b_1 S^{b_2} [(1 - \exp(b_3 T))^{b_4 b_5}] \dots \dots \dots (1)$$

**Table 2.** Site conditions of black spruce plantations compared in this study.

|                             | Fleming and Wood<br>(1996)          | Malik (1998) and<br>Timmer (1999) | Payandeh and Wang<br>(1995)               |
|-----------------------------|-------------------------------------|-----------------------------------|-------------------------------------------|
| Township                    | Kenogaming                          | Iroquois Falls                    | Nipigon and Cochrane                      |
| Geographical<br>location    | 48°49' N/80°38' W                   | 48°10' N/82°00' W                 | 49°03' N/88°15' W to<br>49°05' N/81°02' W |
| Previous<br>forest cover    | Hardwood/<br>mixedwood              | Hardwood/<br>mixedwood            | N/A                                       |
| Soil type                   | N/A                                 | Orthic gleysol                    | N/A                                       |
| Soil physical<br>conditions | Well-drained<br>silty to loamy sand | Fresh moist<br>fine loamy-clay    | N/A                                       |
| Land<br>preparation         | Strip cutting,<br>blading           | Clearcutting,<br>blading          | N/A                                       |

where  $H$  is stand height (m),  $S$  is site index (m),  $T$  is stand age (year), and  $b_i$  are model parameters, with  $b_1 = 16.1822$ ,  $b_2 = 0.2189$ ,  $b_3 = 0.0346$ ,  $b_4 = 2.9237$ , and  $b_5 = S^{0.3273}$  for black spruce.

In contrast with Plonski's growth predictions for natural stands, Payandeh and Wang's (1995) findings showed that under the same site conditions, plantation growth is usually slower in the early years and faster after year 15. Our model predictions for early growth of nutrient-loaded and conventional seedlings of Malik's (1998) and Timmer's (1999) trials revealed a stronger fit with Payandeh and Wang's (1995) model ( $R^2 = 0.98$ ,  $RMSE = 0.09$ ) than with Plonski's (1981) model ( $R^2 = 0.98$ ,  $RMSE = 0.34$ ). This correlation confirms our decision to apply the plantation site index model (figures 3 and 5). Based on Malik's (1998) and Timmer's (1999) data, height growth patterns of nutrient-loaded and conventional seedlings were separated into 2 site index classes, with the nutrient-loaded seedlings showing greater height growth (Figure 3). Biomass production was then calculated for each of the 2 classes.

One concern about Payandeh and Wang's (1995) site index model is that growth may be

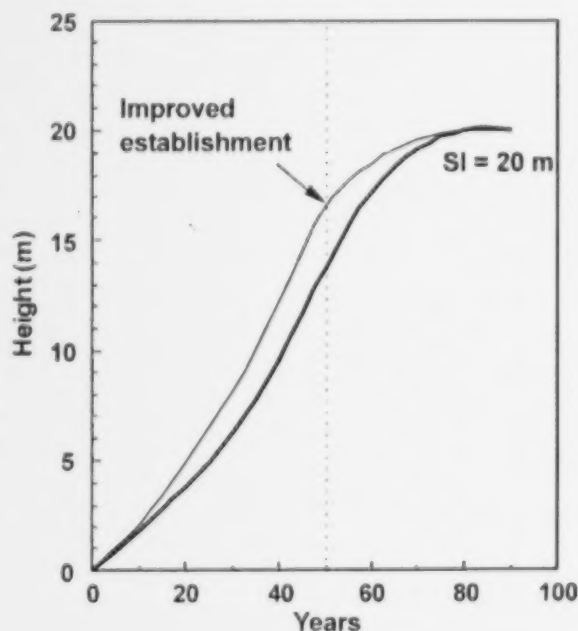


**Figure 4.** Potential shift in a site index (SI) curve resulting from improved plantation establishment (modified from Proe et al. 1994). The arrow indicates higher yield was achieved earlier in the rotation.

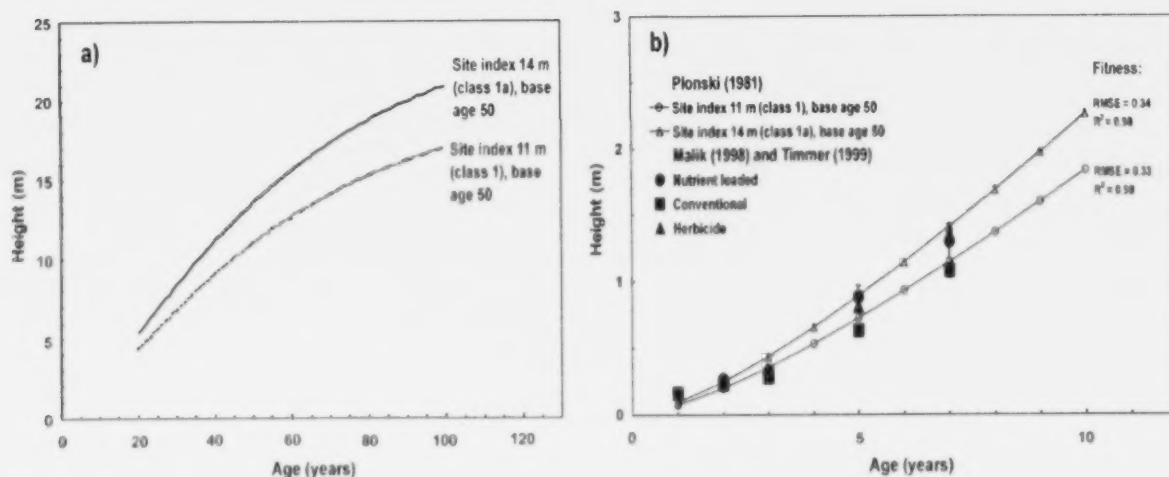


Figure 5. a) Plonski's site index curves (base age = 50) formulated by Payandeh (1991) for natural black spruce stands and b) height growth of conventional and nutrient-loaded seedlings (Malik 1998, Timmer 1999) imposed on Plonski's site index curves extrapolated back to year 0. RMSE = root mean square error.

overestimated for older stands, since the curves did not cover trees older than 40 years. Normally, maximum growth of a species is constrained by site conditions (Miller 1981), which is the foundation of the site index approach (Davis and Johnson 1987). To extend our growth projections, we overlapped the mature phase of Payandeh's (1991) model (developed for natural black spruce stands) with the plantation model ending at year 40 (Figure 6).

### Estimating biomass production

To estimate forest biomass non-destructively, allometric techniques have been developed to relate forest tree biomass to measurable characteristics, such as tree height and diameter at breast height (DBH). In Ontario, Ter-Mikaelian and Korzukhin (1997) comprehensively reviewed published biomass equations for 65 North American tree species. However, none of the models presented in their paper were originally constructed for black spruce in Ontario. Since Alemdag (1983) conducted a systematic study on biomass equations designed specifically for 11 Ontario softwoods, including black spruce, we adopted his model for our calculations. The model assumes the form:

$$M_a = 0.2267(\text{DBH})^2 H \quad \dots\dots\dots(2)$$

where  $M_a$  is aboveground whole tree biomass ( $\text{kg tree}^{-1}$ ), DBH is diameter at breast height (cm), and  $H$  is tree height (m).

Most biomass models estimate tree biomass from DBH. For trees 20 years of age and older, we calculated tree height using Payandeh and Wang's (1995) model (Figure 3) where DBH-height relationships were obtained from Plonski (1981) (Figure 7a). For juvenile trees (heights <1.30 m at

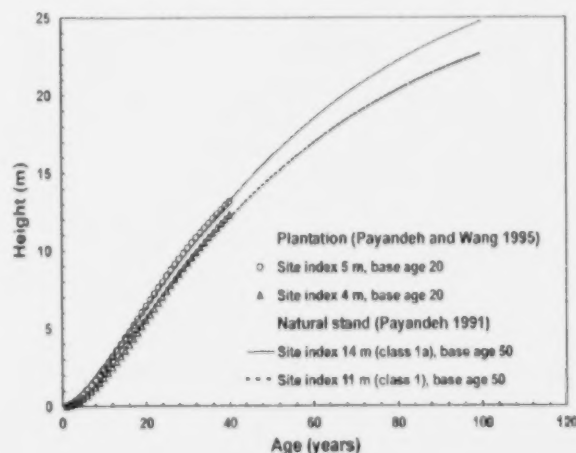


Figure 6. Extension of the plantation site index model (Payandeh and Wang 1995) for black spruce from age 40 to 100 by overlapping with Plonski's site index model (Payandeh 1991).

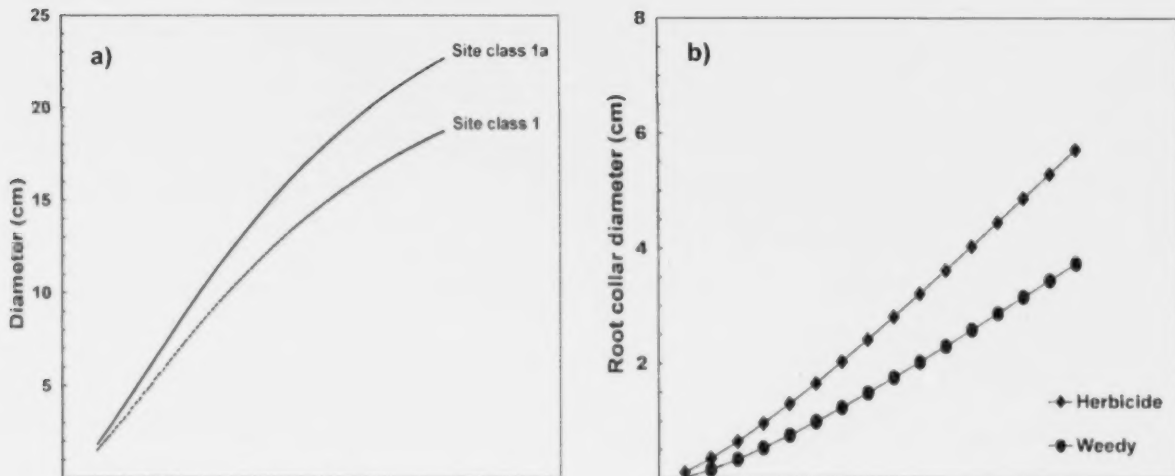


Figure 7. a) Plonski's (1981) diameter growth model for natural stands (trees >1.3 m) of black spruce formulated by Payandeh (1991) and b) relationship between root collar diameter and age for juvenile trees (Fleming and Wood 1996).

breast height), DBH was not applicable. In such cases, we used Wagner and Ter-Mikaelian's (1999) model, where:

$$M_a = 0.5419D^{1.9902} \dots\dots\dots(3)$$

for trees younger than 20 years of age, which relates biomass of juvenile trees to root collar diameters (D) rather than DBH. Root collar diameters were calculated from tree height following Fleming and Wood (1996) (Figure 7b), where:

$$D = 0.0742 + 0.112H \dots\dots\dots(4)$$

with D being root collar diameter (cm) and H being tree height (m).

Alemdag's (1983) model is limited by the lack of equations to determine root biomass or whole tree biomass. Accordingly, we added 17% to the aboveground tree biomass to predict whole tree biomass, as suggested by Birdsey (1992). Kurz et al (1996), in comparison, report that root biomass is about 0.23 of whole tree biomass. One advantage of Plonski's yield tables (1981) is that tree density is provided for stands of various classes at all ages. Accordingly, total biomass yield was calculated as the product of single tree biomass and the number of trees on an area basis.

## Converting biomass to carbon storage

In southern Finland, Laiho and Laine (1997) showed that the carbon concentrations of various components of 3 tree species, including Norway spruce (*Picea abies* (L.) Karst.), ranged from 49.7 to 55.7% (50.9 to 54% for the spruce). The variation among species was not significant. To simplify our calculations, we adopted the widely accepted 50% conversion factor (Freedman et al. 1992, Reichle et al. 1973) to derive carbon content from biomass yield.

## Results and Discussion

### Effect of nutrient loading on height growth

Early height growth of nutrient-loaded seedlings tends to follow the growth curve from Payandeh and Wang's model (Figure 3) more closely than the Plonski growth curve (Figure 5). Nutrient-loaded seedling growth followed the Site Index 5 projection, and conventionally reared seedling growth followed the Site Index 4 curve projection (Figure 3). Thus, by year 15 (the base age of the model), nutrient-loaded trees are 1.0 m taller than conventional trees. By year 40 (the time limit of the model), the difference in height is 2.2 m. By year 60, which is

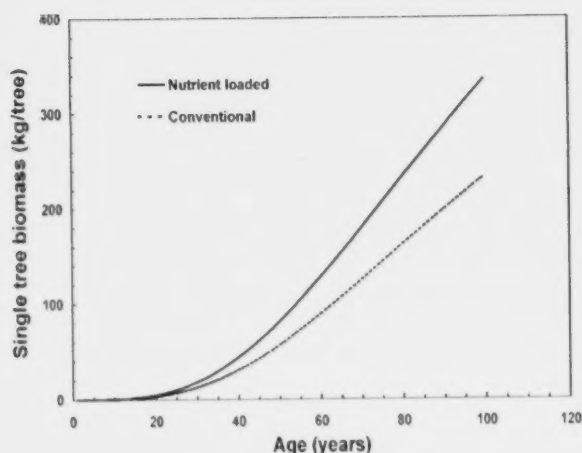


**Figure 8.** Single whole tree biomass growth projection for nutrient-loaded and conventionally cultured black spruce seedlings after outplanting. Aboveground biomass estimated for trees <10 years was derived from Wagner and Ter-Mikaelian (1999); older tree biomass calculations were based on Alemdag (1983). The aboveground tree biomass was multiplied by 1.17 (Birdsey 1992) to include root biomass.

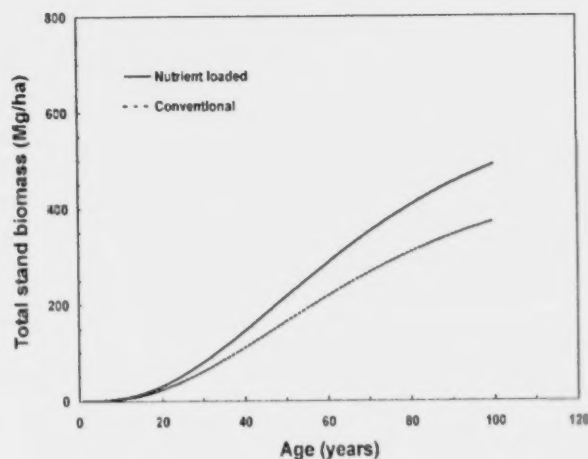


**Figure 9.** Total biomass productivities projected for black spruce plantations originating from nutrient-loaded or conventionally cultured seedlings as the product of single tree biomass and plantation density. Plantation density was estimated using the Plonski yield model (Payandeh 1991).

commonly when black spruce reach merchantable size (15 m) in Ontario, nutrient-loaded trees are 2.5 m taller than conventional trees (Figure 6).

### Biomass and carbon storage

Given that biomass accumulation in single trees follows an exponential pattern, differences in biomass storage of carbon between the two types of plantations also increase with stand age (Figure 8). Since total biomass yield ( $\text{Mg ha}^{-1}$ ) is calculated as the product of single tree biomass and stand density, a similar pattern of total biomass accumulation was projected on an area basis (Figure 9). The potential carbon storage capacity of nutrient-loaded and conventionally reared plantations is shown in Figure 10.

In New Brunswick, Freedman et al. (1992) estimated biomass and biomass carbon in plantations growing on various sites and suggest that intensively managed plantations are much more

productive than unmanaged forests. On average, a typical 60-year-old conifer plantation established on a high-quality site had a net carbon fixation rate that was about 160% higher than that of an average unmanaged stand. In our study, at year 60, estimated carbon storage of the plantations generated from nutrient-loaded seedlings was  $143.1 \text{ Mg ha}^{-1}$ , compared with an estimate of  $108.6 \text{ Mg ha}^{-1}$  for plantations generated from conventional seedlings. Thus, sequestration potential was 31.9% higher, a gain of  $34.6 \text{ Mg ha}^{-1}$  at year 60 (Figure 10b). At this age, plantations generated from nutrient-loaded seedlings would be 9 years ahead of conventional plantations in terms of biomass production or carbon sequestration. These results are similar to those of Freedman et al. (1992) who found that at year 60 carbon reserves were projected at 131 and  $107 \text{ Mg ha}^{-1}$  for high- and medium-quality sites at year 60, respectively (Table 4).

**Table 3.** Flowchart of steps taken, models applied, and references consulted to estimate the effects of nursery nutrient loading on carbon sequestration of black spruce plantations.

| Procedures                                                               | Models used <sup>a</sup>                                                                      | References                                         |
|--------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|----------------------------------------------------|
| Step 1: Collect outplanting performance data                             |                                                                                               | Malik and Timmer 1996<br>Malik 1998<br>Timmer 1999 |
| Step 2: Model juvenile height growth                                     | $H = b_1 S^{b_2} [(1-\exp(b_3 T))]^p$                                                         | Payandeh and Wang 1995                             |
| Step 3: Model juvenile radial growth                                     | $D = a + b H$                                                                                 | Fleming and Wood 1996                              |
| Step 4: Model biomass of young trees (total)                             | $M = a D^b$                                                                                   | Wagner and Ter-Mikaelian 1999                      |
| Step 5: Develop site index model for mature trees                        | $H, D = b_1 S^{b_2} [(1-\exp(b_3 T))]^{b_4}$<br>$H = b_1 S^{b_2} [(1-\exp(b_3 T))]^{b_4 b_5}$ | Payandeh 1991<br>Payandeh and Wang 1995            |
| Step 6: Model aboveground biomass for mature trees                       | $M_a = b (DBH)^2 H$                                                                           | Alemdag 1983                                       |
| Step 7: Add root biomass to aboveground biomass to predict total biomass | $M = (1 + 0.17) M_a$                                                                          | Birdsey 1992                                       |
| Step 8: Convert total biomass to total carbon content                    | $C = 0.50M$                                                                                   | Laiho and Laine 1997                               |

<sup>a</sup> H = tree height (m), T = tree age (year), D = root collar diameter (cm), M = whole tree biomass,  $M_a$  = aboveground tree biomass, C = carbon content, exp = exponential, and s, r, a, b,  $b_1$ ,  $b_2$ ,  $b_3$ ,  $b_4$  and p are regression coefficients.

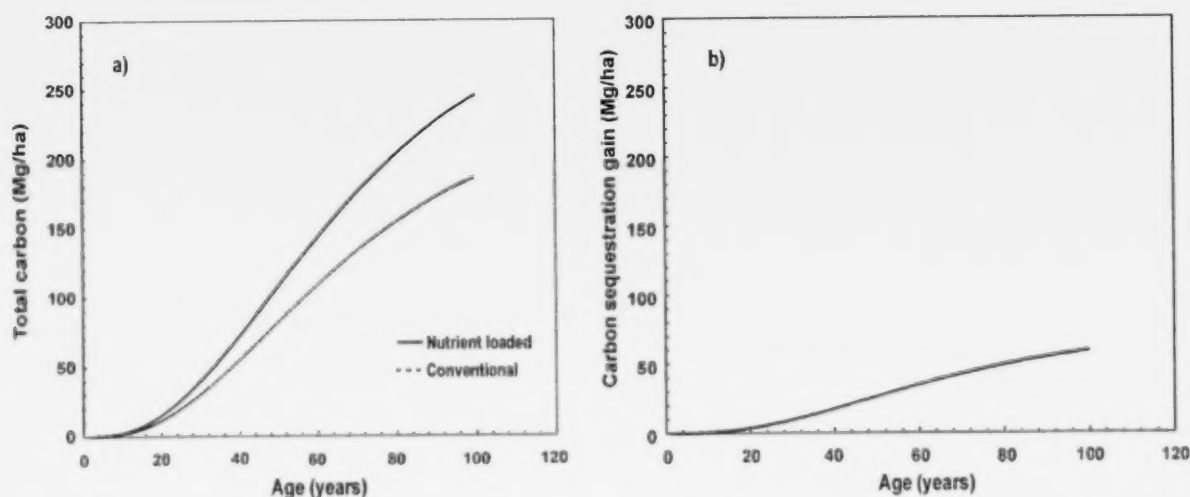


Figure 10. a) Model projection for carbon contents of nutrient-loaded and conventionally cultured black spruce plantations after outplanting and b) estimated gain in carbon sequestration generated by nutrient loading.

Table 4. Estimated carbon sequestration ( $\text{Mg ha}^{-1}$ ) dynamics of black spruce plantations in northern Ontario grown from either conventional or nutrient-loaded seedlings compared with the same species in New Brunswick (Freedman et al. 1992).

|                                        | Time (years) |      |      |      |       |       |       |       |       |       |
|----------------------------------------|--------------|------|------|------|-------|-------|-------|-------|-------|-------|
|                                        | 10           | 20   | 30   | 40   | 50    | 60    | 70    | 80    | 90    | 100   |
| <b>This study</b>                      |              |      |      |      |       |       |       |       |       |       |
| Conventional                           | 1.7          | 11.5 | 30.2 | 54.8 | 81.9  | 108.6 | 113.0 | 154.2 | 172.0 | 186.3 |
| Nutrient loaded                        | 2.3          | 15.1 | 39.8 | 72.3 | 108.0 | 143.1 | 175.3 | 203.3 | 226.7 | 245.6 |
| Carbon sequestration gain <sup>a</sup> | 0.6          | 3.7  | 9.6  | 17.5 | 26.1  | 34.6  | 42.3  | 49.1  | 54.7  | 59.3  |
| <b>Freedman et al. (1992)</b>          |              |      |      |      |       |       |       |       |       |       |
| Good site                              |              |      |      |      |       | 131.0 |       |       |       |       |
| Medium site                            |              |      |      |      |       | 107.0 |       |       |       |       |
| Poor site                              |              |      |      |      |       | 64.5  |       |       |       |       |

<sup>a</sup> Carbon sequestration gain was calculated as the difference between nutrient-loaded and conventional treatment sites. Mg = 1 000 000 gram

## Conclusions

Nutrient loading is an inexpensive means of increasing seedling growth after planting, compared with chemical or mechanical site preparation. Six years after planting, nutrient-loaded seedlings had better height growth and biomass production than conventional seedlings. In addition, the effect of nutrient loading on growth is similar to if not greater than the effect of herbicide treatment at site preparation. Published studies show that trees that are larger at the early plantation stage maintain their superior growth and size in later years. On this basis, we estimated that plantations regenerated from nutrient-loaded seedlings could sequester almost 32% more carbon (or CO<sub>2</sub>) at rotation age (60 years) than those regenerated from conventional seedlings. Based on their work in New Brunswick, Freedman et al. (1992) indicated that this is equivalent to shifting stand productivity from medium to high-quality sites.

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